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REPORT No. 557

PRELIMINARY TESTS IN THE N. A. C. A. FREE-SPINNING WIND TUNNEL

By C. H. ZIMMERMAN

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1936

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s² or 32.1740 ft./sec.²

m, Mass $=\frac{W}{g}$

I, Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu.ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o}=\frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of *c.p.* from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_o, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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By C. H. ZIMMERMAN
Langley Memorial Aeronautical Laboratory

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By C. H. Zimmerman

SUMMARY

Typical models and the testing technique used in the N. A. C. A. free-spinning wind tunnel are described in detail. The results of tests of two models afford a comparison between the spinning characteristics of scale models in the tunnel and of the airplanes that they represent.

The models are built of balsa wood and ballasted with lead to the proper mass distribution. A clockwork delayed-action mechanism is mounted in the model to move the control surfaces during the spin.

In steady-spin tests, observations are made of the rate of rotation and of the air speed necessary to hold the model at test height. Moving-picture records are taken from which the spinning attitudes are obtained. In recovery tests, moving-picture records are taken of the model from the instant the controls move until recovery is effected or failure to recover is definite.

The models of the XN2Y–1 and F4B–2 airplanes gave good approximations to the spinning characteristics of the airplanes, in both steady spins and recoveries. Since these models were scaled from somewhat similar biplanes, no conclusions are drawn as to the reliability of model results in general.

INTRODUCTION

Although the problem of the spin has been the object of a great deal of research, airplanes of recent design are occasionally found to have undesirable spinning characteristics. The prevalence of this condition is the result of a combination of factors that may be summarized as follows: A very great amount of experimental work is necessary before spinning characteristics can be accurately predicted by analysis; and designers are unwilling to go, possibly unnecessarily, to extreme measures to insure good spinning characteristics. Consequently, it has become very desirable to develop a method of determining the spinning characteristics of an airplane while it is in the design stage.

About 10 years ago members of the N. A. C. A. laboratory staff studied means of improving the spinning characteristics of two airplanes by noting the behavior of dynamic scale models when launched in spins from the top of a balloon shed. (See reference 1.) Although the method showed promise, it was abandoned because of the difficulty of making satisfactory tests with the short free drop available (105 feet). There was also considerable doubt at the time concerning the fidelity with which scale models indicated full-scale behavior.

This method of studying spinning was adopted by research workers in England, who obtained a great deal of interesting and valuable information (reference 2). They likewise were hampered by the limited free drop available and, in an effort to avoid this restriction, built a small vertical wind tunnel in which it was possible to cause models to continue spinning for long periods of time without restraint other than that of the air. The model tunnel showed such promise that a 12-foot-diameter vertical tunnel was built for testing models of sufficient size for practical results (reference 3). This tunnel has been in operation since 1932.

The N. A. C. A., realizing the need of a satisfactory method of predicting spinning behavior and aware of the value of the results of the tests in the British free-spinning tunnel, constructed the tunnel, the operation of which is described in this report. The tunnel is expected to provide American designers with a ready means of determining whether changes are necessary in their airplane designs without the expense and danger of full-scale flight tests and the expense and delay incident to changes after construction.

The tunnel was completed in September 1934. Alterations to improve the air flow, velocity and turbulence surveys, and a calibration of the air-speed indicator were completed in March 1935. The first spin tests were made in April 1935. A large number of tests, both of steady spins and of recoveries, have been made to obtain data from which comparisons can be made between the spinning behavior of the XN2Y–1 and the F4B–2 airplanes (references 4 and 5) and scale models of them. These tests served as a calibration of the tunnel and the results are therefore included in this report.

DESCRIPTION OF MODELS

Dimensional characteristics.—The models used are generally $\frac{1}{10}$ to $\frac{1}{16}$ scale. (See fig. 1.) The size of the models is limited by the wing span and the wing loading. The maximum span allowable is about 36 inches; the maximum wing loading is about 1.3 pounds per square foot. Since the model wing loading must be equal to the airplane wing loading multiplied by the scale ratio (reference 6), 1.3 pounds per square foot corresponds to 13 pounds per square foot for the airplane when the model is $\frac{1}{10}$ scale or 21 pounds per square foot when the model is $\frac{1}{16}$ scale.

Balsa wood is the usual structural material because of its low density. It is necessary to hollow out the after portion of the fuselage and to cut out a large portion of the wood in the wings to permit proper mass distribution. The wing cut-outs are covered with silk tissue paper. The leading and trailing edges and tips of the wings are fitted with strips of spruce, pattern pine, or bamboo inset into the edge of the balsa to prevent disfigurement from accidental blows or from striking the safety netting. Lead is used for ballast.

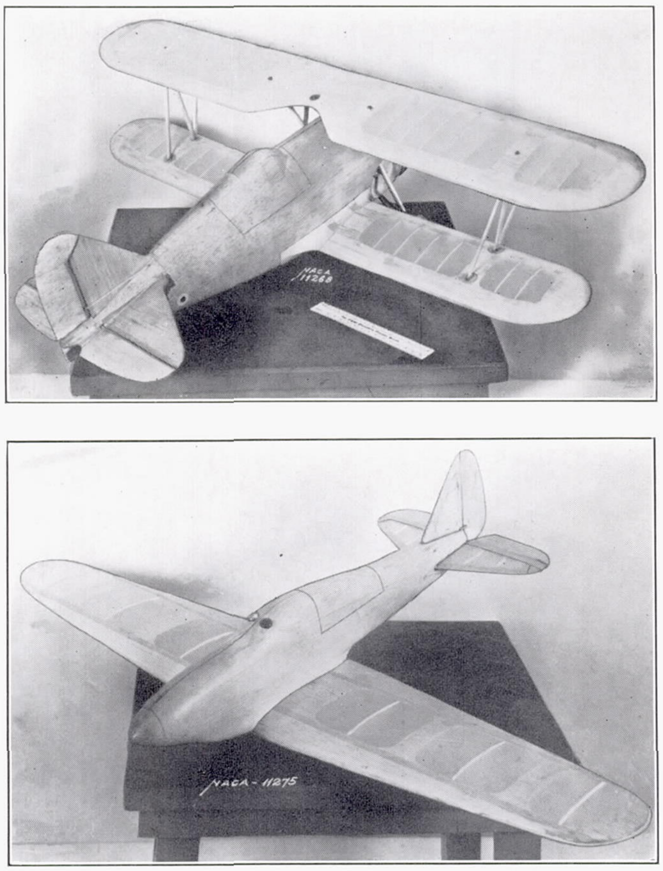


FIGURE 1.—Typical models used in the free-spinning tunnel.

Exact scale models are very expensive. Furthermore, it is impracticable to attempt to maintain an extreme degree of dimensional accuracy in models that must be built of balsa wood and be subjected to the rather rough treatment incidental to free-spinning tests. Consequently, tolerances somewhat larger than normal in model construction are permitted. Tolerances that appear to be satisfactory are ± 0.01 inch on wing- and tail-surface profiles, ± 0.02 inch on all other dimensions under 6 inches, and ± 0.03 inch on all other dimensions over 6 inches. Angular relationships are held to $\pm 0.5°$. Details of fittings, air scoops, propellers, and other protuberances are omitted.

The fuselage, tail surfaces, and landing gear are finished with clear shellac, sanded smooth. The wings are finished with clear shellac or with wax, depending on whether difficulty is encountered in keeping the wings sufficiently light for the required mass distribution.

Mass characteristics.—Models to be used for free-spinning tests must be scaled from the airplane in mass distribution as well as in dimensional characteristics. In order to preserve dynamic similarity the weight of the model must be that of the airplane multiplied by the scale ratio to the third power, the center of gravity must be in the same relative location as in the airplane, and the moments of inertia must be those of the airplane multiplied by the scale ratio to the fifth power. Values of weight and moment of inertia are corrected for the difference between the air density in the tunnel and the density at the altitude at which the full-scale tests have been or are expected to be made.

The weight, the center-of-gravity location, and the moments of inertia are adjusted to the proper values by suitably disposed lead weights. The center-of-gravity location is determined by suspending the model by a thread in two or more attitudes and determining the point of intersection of vertical lines passing through the point of support.

The distribution of mass is determined by swinging the model as part of a compound pendulum and timing the oscillations. A knife-edge mounted in a vacuum chamber (see fig. 2) serves as support for the pendulum. The moments of inertia are determined in this manner about the X, Y, and Z axes of the model and also about an axis in the plane of symmetry at 45° to the X and Z axes. In the cases of airplanes of which the full-scale moments of inertia have been determined by swinging tests, the model is swung in air at sea-level density and its moments of inertia so determined are brought into proper scale relationship with the virtual moments of inertia of the airplane (reference 7). In the cases of other models the true moments of inertia are determined by swinging the model at several reduced air densities and extrapolating the plots of moment of inertia against density to zero density. The true moments of inertia so determined are brought into proper scale relationship with the calculated true moments of inertia of the airplane.

The accuracy of the means of measurement is such that the quantities can be determined within the following limits:

Weight	±0. 1 percent.
Center-of-gravity location	±0. 01 inch.
Moment of inertia	±3 percent.

Because of the effects of humidity upon the weight and mass distribution and the difficulty often encountered in placing ballast to give exactly the desired values, the mass quantities are not kept within the limits of accuracy of the measurements, but are held to the desired values within the following limits:

Weight	±1 percent.
Center-of-gravity location	±1 percent of chord.
Moments of inertia	±5 percent.

Automatic-control mechanism.—In order that the behavior of models during recovery from the spin may be studied, a clockwork mechanism has been developed for moving the control surfaces while the model is spinning. This mechanism consists essentially of a watch spring, gears, and an escapement mechanism that drive a movable table. The table, in turn, carries small projecting plugs that actuate cam mechanisms and permit the control surfaces to be moved by springs. Three sets of cam mechanisms and related parts are provided so that each of three controls can be moved independently of the other two. The control surfaces can be caused to move either slowly or quickly and in any order desired with intervals between the movements of different controls as great as one-half minute by disposing the projecting plugs suitably in the movable table.

The mechanism is connected to the control surfaces by threads that transmit the movement. In order that observers may know the exact instant of movement of the control surface a small paper disk is clamped lightly to the side of the fuselage and connected to the control horn by a thread. Movement of the control horn pulls the paper disk free and it trails behind the spinning model.

TESTING TECHNIQUE

Launching the model.—At the beginning of a test the model is mounted upon a launching spindle about the axis of which it is free to rotate. This spindle is on the end of a wooden rod and is held in the center of the tunnel by one of the operators standing in the observation chamber. With the spindle vertical the attitude of the model is such that the fuselage axis is approximately 35° to the horizontal, nose down, and the wings are 10° to the horizontal with the left wing tip the lower (for a right spin). When the model is in this attitude, air flowing upward through the tunnel causes it to rotate fairly rapidly. The air speed is increased by a second operator until the air force on the model is equal to its weight. The model then automatically disengages itself from the spindle and continues to float in the air stream entirely free of mechanical restraint. The launching spindle is immediately withdrawn from the tunnel. The air speed is adjusted until it just equals the rate of descent the model would have in still air and the model is at approximately eye level in the test section.

Steady spins.—With the model spinning steadily in the tunnel, observations are made of the air speed and rate of rotation; the air speed is taken from a calibrated tachometer and the rate of rotation is determined by noting with a stop watch the time required for 50 turns in the spin. Moving pictures are taken of the spinning model for a permanent record of its spinning attitude and any oscillatory tendencies or unsteadiness. The pictures are taken on 16 mm film at the rate of 64 per second. About 10 turns of the spin are photographed.

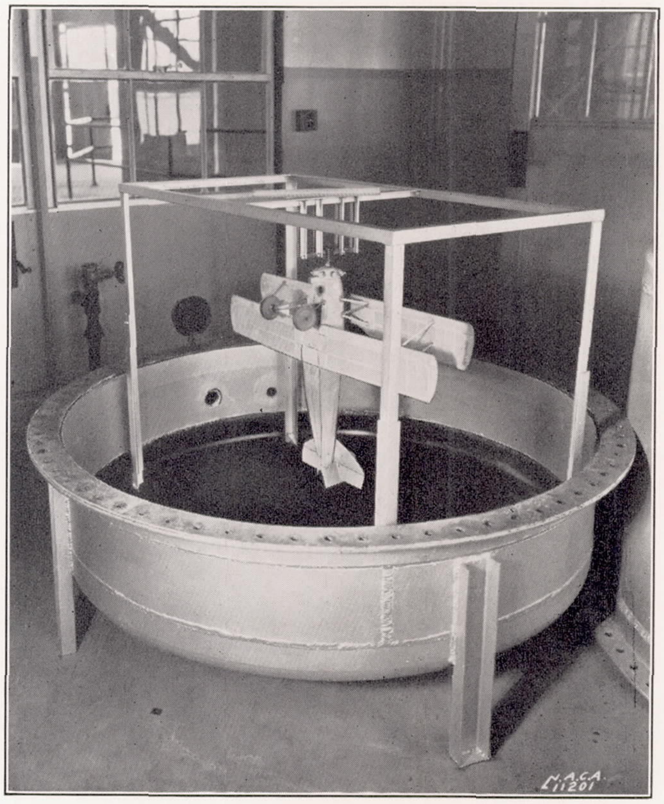


FIGURE 2.—Model-swinging gear.

After the observations have been made, the model is lowered into a net held in the air stream by one of the operators or into a large bowl-shaped net at the bottom of the test section. When lowered into the large net, the model is retrieved with a long-handled clamp.

Recoveries.—When making recovery tests, the clockwork mechanism is wound, set to operate the controls after a time interval of approximately 1 minute, and started before the model is launched. The model is then launched as previously described. About 2 seconds before the controls are to move, the camera is started and pictures are taken continuously at the rate of 16 per second until the model has dived into the netting or has definitely established a new spinning condition. For comparison with the camera records, one of the operators estimates the number of turns from the time the controls operate until the spin ceases. At least two, and frequently more, of these recovery tests are made for each test condition. The first recovery for each test condition is made with the model well down in the bowl-shaped net to determine whether the model tends to go immediately into a stalled glide, carrying it rapidly toward the side of the tunnel, or whether it goes into a nearly vertical dive. One or two recoveries cautiously made in this manner prevent unnecessary damage to the model. When the typical behavior of the model for the particular test condition has been determined, the model is allowed to start recovery as high in the test section as the trial tests have indicated to be safe.

Reduction of data.—The data from a steady-spin test consist of the film record (fig. 3), the air speed, and the rate of rotation. The angles of the fuselage (X) axis and the span (Y) axis to the horizontal are measured on the film using a film-viewing machine provided with a cross hair and a protractor. The intersections of the fuselage axis with the nose and tail are used as reference points in determining the fuselage-axis angle; corresponding points on the wing tips, which define a line parallel to the span axis, serve as reference points in determining the span-axis angle. Experience has shown that the angles can be readily obtained to within $\pm 1°$ by this method. The angles so measured are designated as θ and ϕ, respectively, where θ is the angle of the fuselage axis to the horizontal, negative when the model is inclined nose downward; and ϕ is the angle of the span axis to the horizontal, positive when the left wing is higher than the right.

The radius of the spin is calculated from the rate of rotation and the value of θ on the assumption that the resultant aerodynamic force on the model is perpendicular to the X and Y axes. That this assumption is close to the true condition has been found to be the case with the N. A. C. A. spinning balance (reference 8). On this basis the radius is determined as in reference 9 by the relationship,

$$\text{Radius} = \frac{g \tan(-\theta)}{\Omega^2}$$

where g is the acceleration of gravity.

Ω, the rate of rotation in radians per second. In a number of cases of full-scale data this approximate equation has been found to give the true radius to within ± 10 percent, except for unusually large angles of sideslip. For most cases it is within ± 3 percent of the true value.

The angle of sideslip in the spin is determined from the relationship

$$\beta = \phi - \sigma$$

where β is the angle of sideslip equal to the $\sin^{-1}$ v/V.

σ, the helix angle equal to the $\sin^{-1}$ Ω radius/V.

This relationship is true to within $\frac{1}{2}°$ or less for spinning attitudes.

The angle of attack is determined from the relationship

$$\alpha = 90° - (-\theta)$$

This equation is an approximation, giving values of α from 1° to 2° higher than the true value for ordinary spinning attitudes. This discrepancy increases with the deviation of the wings from the horizontal, computed values being as much as 5° or 6° too high with large amounts (15° to 20°) of inward sideslip, and 3° to 4° too low with large amounts of outward sideslip.

The data from a recovery test consist of film records of one or more recoveries (fig. 4) and the observer's estimate of the number of turns required for recovery. The number of turns made by the model from the time the signal disk is pulled from its clamp until rotation ceases is obtained from the film and compared with the observer's estimate. In all recoveries for which film records are obtained the film-record value is used for the recorded data. In other cases the observer's estimate is used. The turns can be determined to within one-quarter of a turn from the film record. The observer's estimate is generally within one turn of the value obtained from the film record.

COMPARISON BETWEEN AIRPLANE SPINNING CHARACTERISTICS AND THE CHARACTERISTICS OF SCALE MODELS IN THE TUNNEL

One of the principal reasons for abandonment by the N. A. C. A. of the method of dropping models for spin study was doubt concerning the fidelity with which scale models indicated the spinning behavior of the airplanes from which they were scaled. When dynamic similarity is preserved, the Reynolds Number of the model is equal to that of the airplane multiplied by $N^{\frac{3}{2}}$ where N is the scale ratio ($\frac{1}{10}$, $\frac{1}{12}$, etc.). Furthermore, it is impracticable to reproduce the airplane in exact detail in a scale model. Comparisons between results from the N. A. C. A. spinning balance and full-scale flight tests have indicated considerable scale effect upon aerodynamic characteristics in spinning attitudes (references 8, 10, and 11). Tests in the British free-spinning tunnel have also given indications of scale effect that must be carefully taken into account in interpreting model free-spinning results (references 3 and 12).

In view of the uncertainty existing about the reliability of the results of model tests, it was thought highly desirable that tests be made in the N. A. C. A.

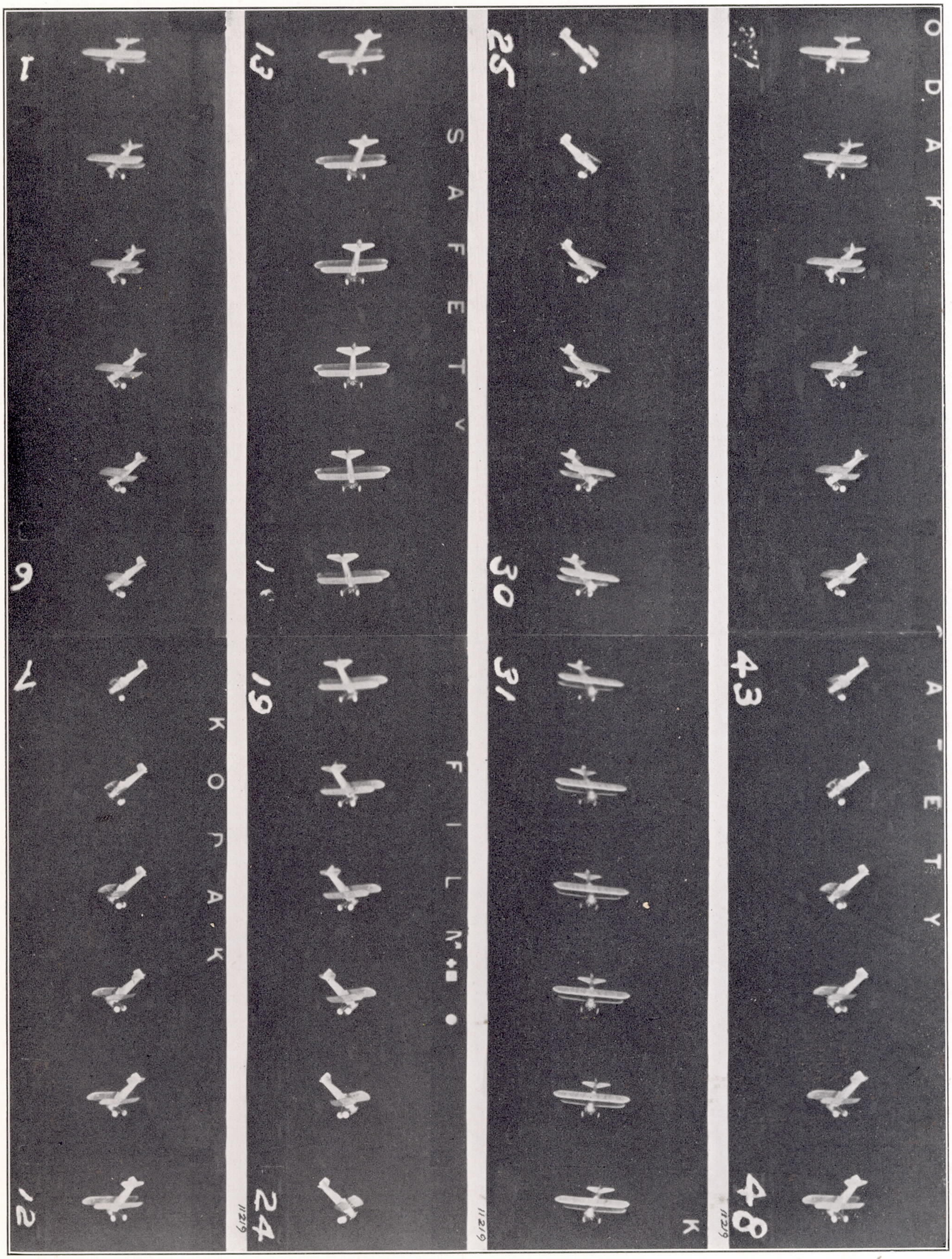


FIGURE 3.—Portion of a film record of a steady spin.

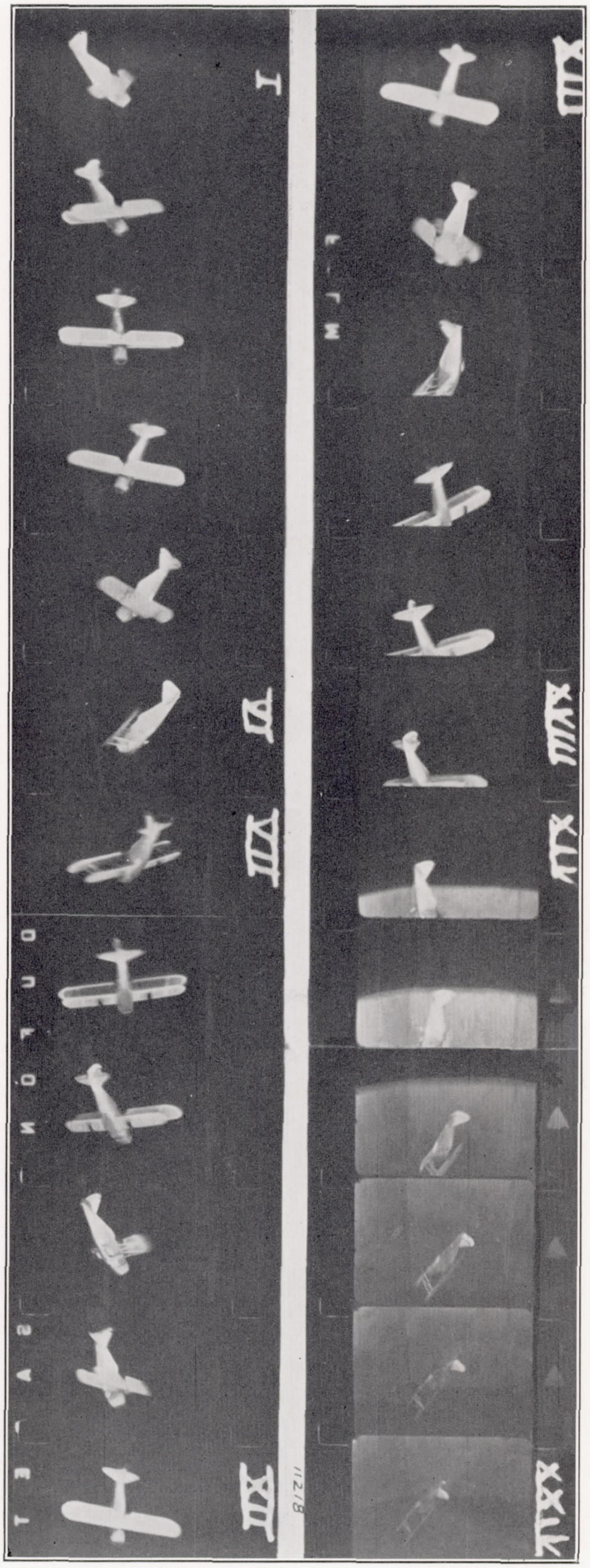


FIGURE 4.—Portion of a film record of a recovery.

free-spinning tunnel with models of airplanes for which the full-scale spinning characteristics are well known. Such tests should indicate the accuracy of the model results and the corrections that should be made to allow for the difference between model and full-scale behavior. Such a series of tests was also considered advisable as an opportunity to acquire experience in operation of the tunnel and to develop the testing technique.

The spinning characteristics of an XN2Y–1 and an F4B–2 airplane have been thoroughly studied by the N. A. C. A. (references 4 and 5). A 1/10-scale model of the XN2Y–1 and a 1/12-scale model of the F4B–2 were accordingly built and tested both for behavior in steady spins and for recovery characteristics.

MODELS

The XN2Y–1 model.—The 1/10-scale model of the XN2Y–1 is shown in figure 5. A drawing of the airplane is included in reference 4. The model was

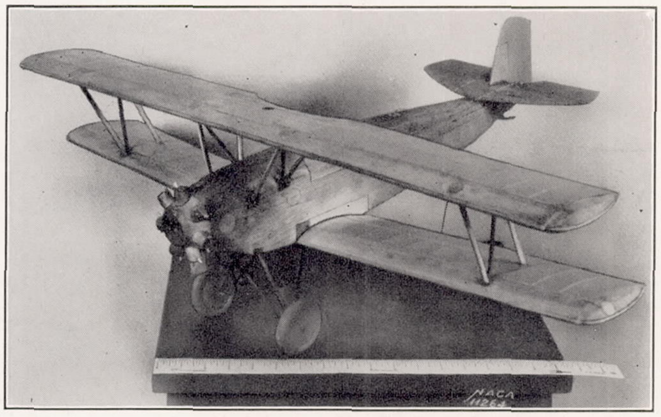


FIGURE 5.—One-tenth-scale model of the XN2Y–1 airplane.

originally made entirely of balsa wood except for the bamboo struts and the silk tissue paper used to cover the wings where the wood was removed for lightness. Dimensions were held to ±0.01 inch. The control mechanism was mounted just back of the wing cellule.

The original balsa tail surfaces, which were very thin and insecurely attached to the fuselage, were replaced by pattern-pine surfaces after the first trial of the model in the tunnel. The original wing cellule was used for the series of steady-spin tests but was demolished in a crash before recovery tests were started. A new wing cellule was built up with spruce spars and bamboo tips for added strength. It was found necessary to hollow out these wings until they were virtually shells to bring the moment of inertia about the fuselage axis to its proper value. As a result the tip of each wing warped outboard of the interplane strut attachments giving from 1/2° to 1° washout at the extreme tip. One steady-spin test, as a check, and all the recovery tests were made with this latter wing cellule.

The F4B–2 model.—The 1/12-scale model of the F4B–2 is shown in figure 6. A three-view drawing and photographs of the airplane are given in reference 5. In the construction, dimensions were held to ±0.01 inch. The wings were built up with spruce spars, ribs, and trailing-edge pieces and were covered with silk tissue paper. The leading portions and the tips were balsa. Bamboo strips were inset into the tips to prevent damage from contact with the safety netting. The leading edges were unprotected. The ribs, spars, leading portions, and tips were hollowed out for lightness. The after portion of the fuselage was hollowed out. The control mechanism was mounted at the center of gravity, access to it being provided by a door in the side of the fuselage.

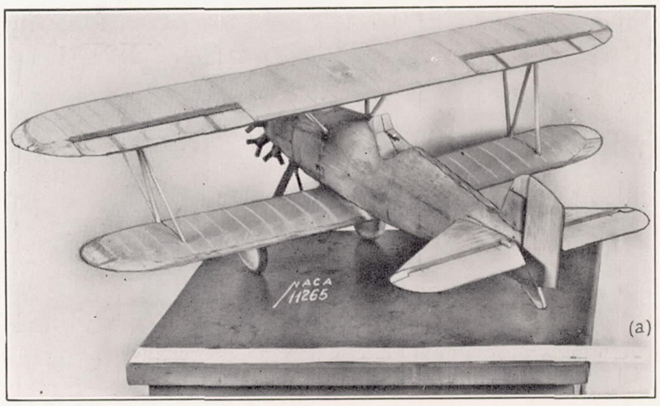
The tail surfaces were balsa, reinforced with spruce. Three interchangeable sets of surfaces were provided, which were held to the fuselage by close-fitting hardwood dowels. The various tail-surface combinations are shown in figure 6. They are designated as the F4B–2 surfaces; the F4B–2 stabilizer with F4B–4 fin and F4B–3 rudder (hereinafter referred to as the F4B–4 fin and rudder, as in reference 5); and the F4B–4 fin and rudder with the F4B–2 stabilizer set on the fin at a height corresponding to 1.54 feet (full-scale) above its normal location. In addition to these combinations, two auxiliary fins similar to those designated as fin 2 and fin 3 in reference 5 were provided.

This model was provided with movable ailerons made carefully to scale not only as regards general dimensions but also as regards the nose shape, the hinge-axis location, and the slot between the aileron and the wing. The ailerons were held in place by copper-wire hinges and the neutral settings were maintained by tack-gluing the aileron to the wing.

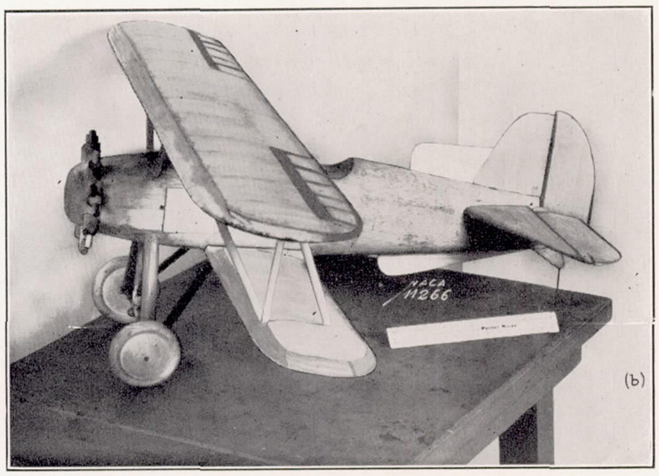
During the course of the tests, which involved approximately 250 spins, it was necessary to repair the wing tips a number of times and once to make extensive repairs to the entire wing cellule. The leading portions and the tips were disfigured somewhat through contact with the safety netting and in making repairs. It has been found impracticable to maintain close tolerances on repairs.

TEST CONDITIONS

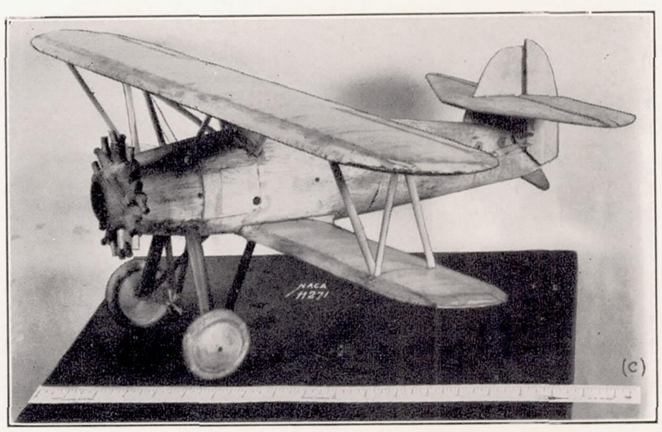
Steady spins.—In addition to the test conditions given in table I for the XN2Y–1 model, steady spins were made with rudder settings 41°, 18°, and 4° with the spin, elevator 24° up, with ballast at the wing tips; and rudder setting 41° with the spin, elevator 26.5° down, with ballast at the wing tips.



(a) Original surfaces.



(b) F4B–4 surfaces and auxiliary fins 2 and 3.



(c) F4B–4 surfaces and intermediate stabilizer.

FIGURE 6.—One-twelfth-scale model of the F4B–2 airplane.

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Normal loading corresponded to the following true mass distribution values for the XN2Y-1 airplane when operated at 6,000 feet altitude:

Weight	1,762 pounds.
A	808 slug-ft.^{2}
B	1,114 slug-ft.^{2}
C	1,501 slug-ft.^{2}
C_g	0.34.
$\frac{z}{c}$	−0.02.

where A, the moment of inertia about the X axis, equal to mk_X^2.

B, the moment of inertia about the Y axis, equal to mk_Y^2.

C, the moment of inertia about the Z axis, equal to mk_Z^2.

C_g, the center-of-gravity coefficient, the ratio of the distance of the center of gravity back of the leading edge of the mean aerodynamic chord to the length of the mean aerodynamic chord.

$\frac{z}{c}$, the ratio of the distance of the center of gravity below the thrust line to the length of the mean aerodynamic chord.

For the loading condition designated "ballast at tips" a weight corresponding to 18 pounds on the airplane was added to each lower wing tip bringing the true mass values to:

Weight	1,798 pounds.
A	1,012 slug-ft.^{2}
B	1,114 slug-ft.^{2}
C	1,705 slug-ft.^{2}
C_g	0.34.
$\frac{z}{c}$	−0.02.

In addition to the test conditions listed in table II for the F4B–2 model, tests were made with the rudder 30° and 15° with the spin, neutral, and 15° and 30° against the spin for elevator settings of 28.3° up, 15° up, neutral, 15° down, and 30.5° down with the normal+radio+raft loading and with the F4B–2 and F4B–4 fin and rudder combinations. In table II control settings are based on maximum deflection of the rudder of ±30°, maximum deflection of the elevator 28.3° up and 30.5° down, and maximum deflection of the ailerons 23° up and 16° down. The setting of the stabilizer relative to the thrust line was zero in all cases.

The mass distribution of the model for the specified loading conditions corresponded to the following true airplane mass distributions at a test altitude of 8,500 feet:

Stripped, F4B–4 fin and rudder:

Weight	2,728 pounds.
A	1,041 slug-ft.^{2}
B	1,876 slug-ft.^{2}
C	2,457 slug-ft.^{2}
C_g	0.34.
$\frac{z}{c}$	−0.03.

Normal+radio+raft, F4B–4 fin and rudder:

Weight	2,915 pounds.
A	1,078 slug-ft.^{2}
B	1,876 slug-ft.^{2}
C	2,455 slug-ft.^{2}
C_g	0.33.
$\frac{z}{c}$	−0.03.

Carrier overload, F4B–4 fin and rudder:

Weight	3,334 pounds.
A	1,131 slug-ft.^{2}
B	1,899 slug-ft.^{2}
C	2,426 slug-ft.^{2}
C_g	0.34.
$\frac{z}{c}$	−0.03.

Recoveries.—The recovery test conditions for the XN2Y–1 model are given in table III. In all recovery tests the controls were moved sharply and simultaneously from the original to the final setting listed. The settings specified are based on maximum rudder settings of ±41° and on maximum elevator settings of 24° up and 26.5° down.

The recovery test conditions for the F4B–2 are given in table IV. The original setting in each case during the steady spin was rudder full with the spin, elevator up, ailerons neutral. In all tests the surfaces were moved sharply and simultaneously to the setting listed in table IV.

RESULTS

Steady spins.—Results of the steady spins of the XN2Y–1 airplane and model are given in figures 7 to 11. For those cases in which direct comparisons were obtained, average values of airplane and model results are given in table I. The full-scale data were taken from a series of tests the results of which have not been published. The model data were obtained from observations and film records as described in the portion of this report dealing with the reduction of steady-spin data. All model data are listed as their full-scale equivalents, model values having been transformed to the full-scale equivalents by the relationships:

$$V_A = \frac{V_M}{\sqrt{N}}$$

and

$$\text{radius}_A = \frac{\text{radius}_M}{N}$$

where, subscript A refers to the airplane.
subscript M refers to the model.

Results of the steady spins of the F4B–2 airplane and model are given in figures 12 to 21. For those cases in which direct comparisons were obtained, average values of airplane and model results are given in table II. The full-scale data are taken from reference 5. All model data are listed as their full-scale equivalents.

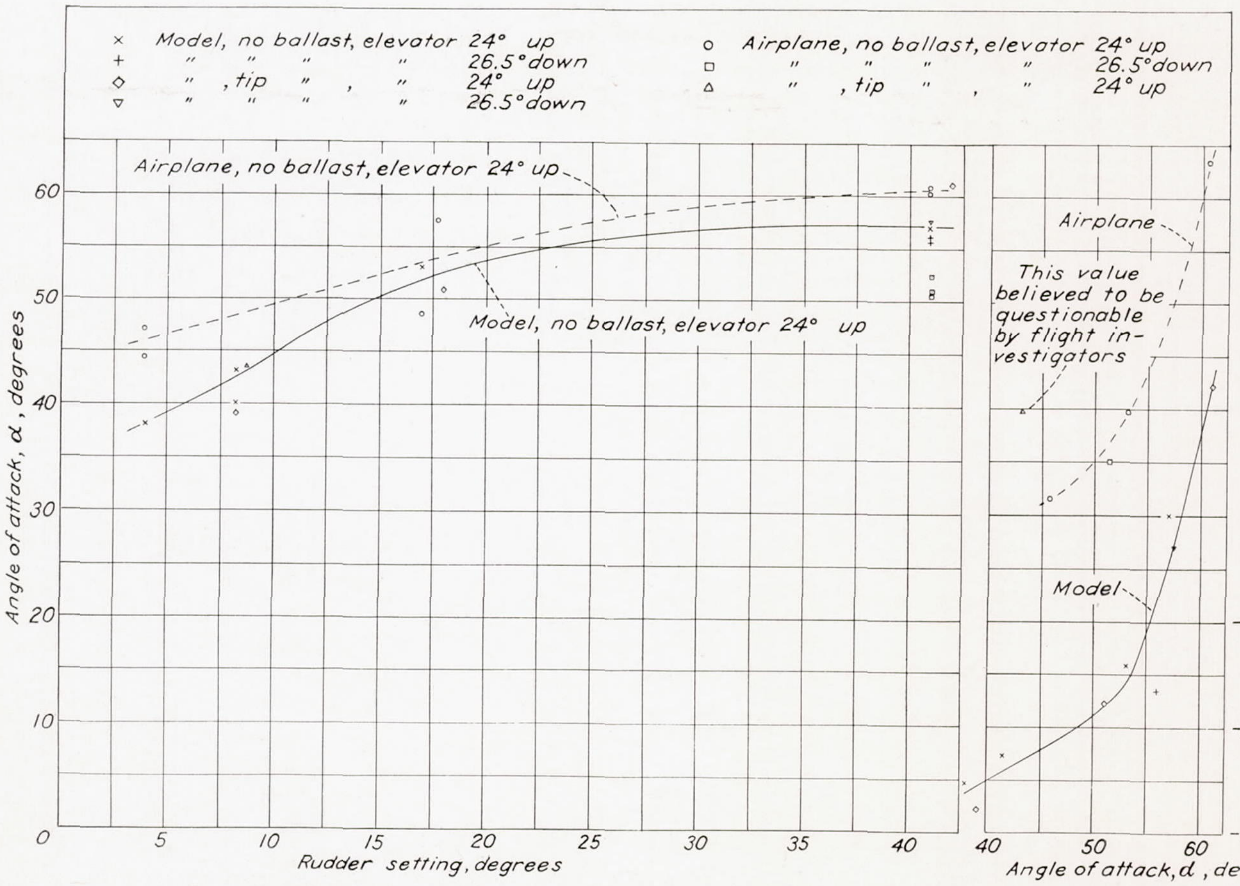


FIGURE 7.—Variation of angle of attack with rudder setting. XN2Y-1.

FIGURE 8.—Variation of angle of sideslip with angle of attack. XN2Y-1.

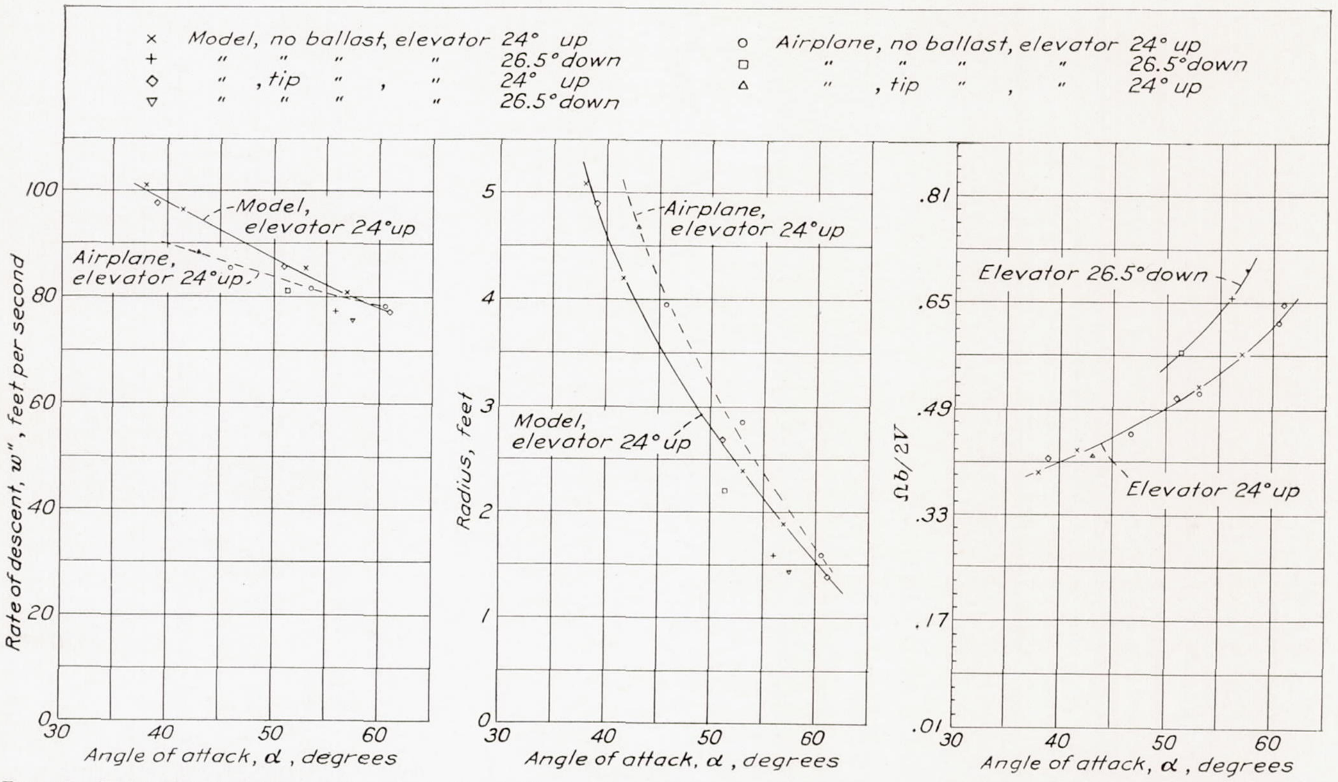
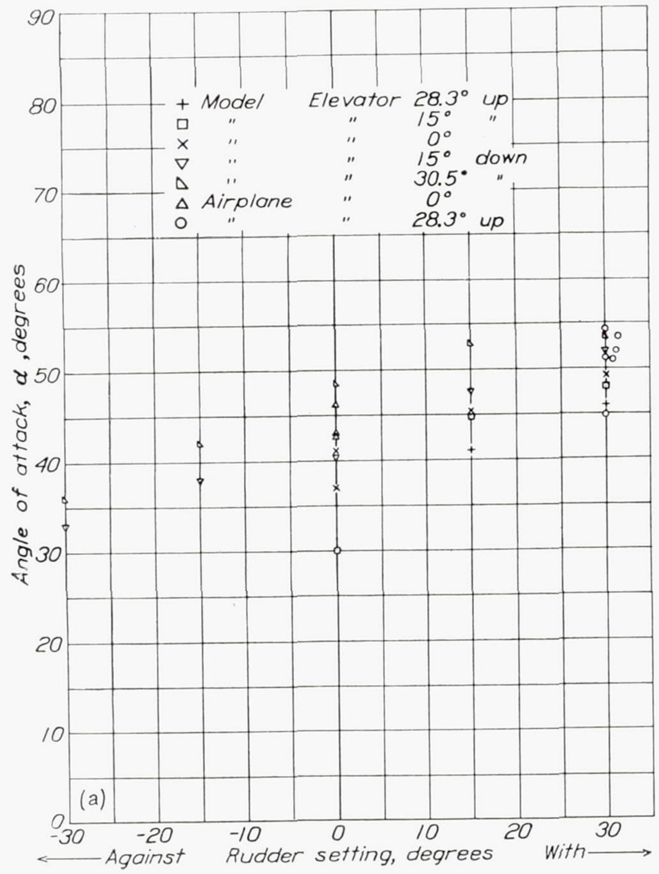


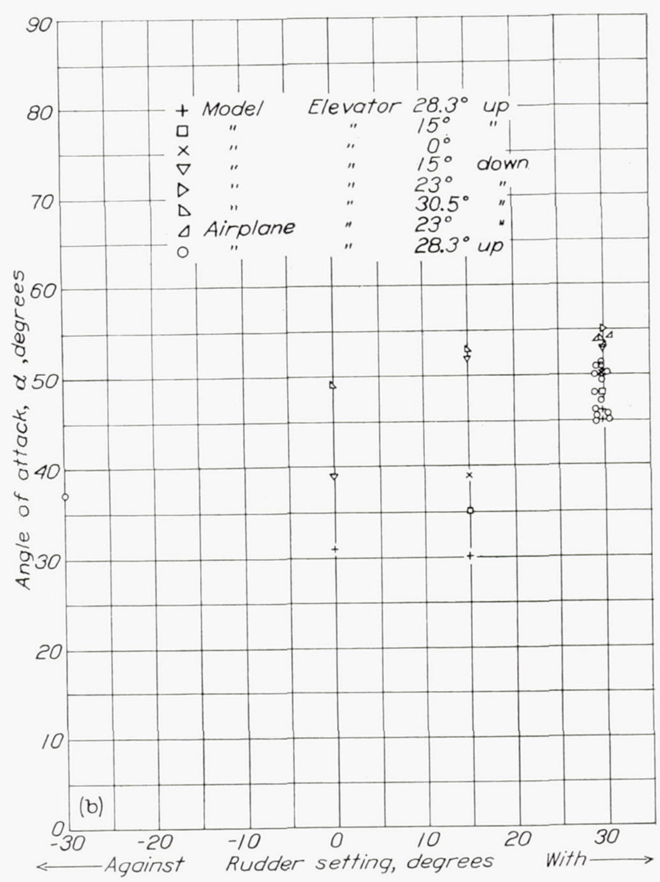
FIGURE 9.—Variation of rate of descent with angle of attack. XN2Y-1.

FIGURE 10.—Variation of radius with angle of attack. XN2Y-1.

FIGURE 11.—Variation of $\Omega b/2V$ with angle of attack. XN2Y-1.

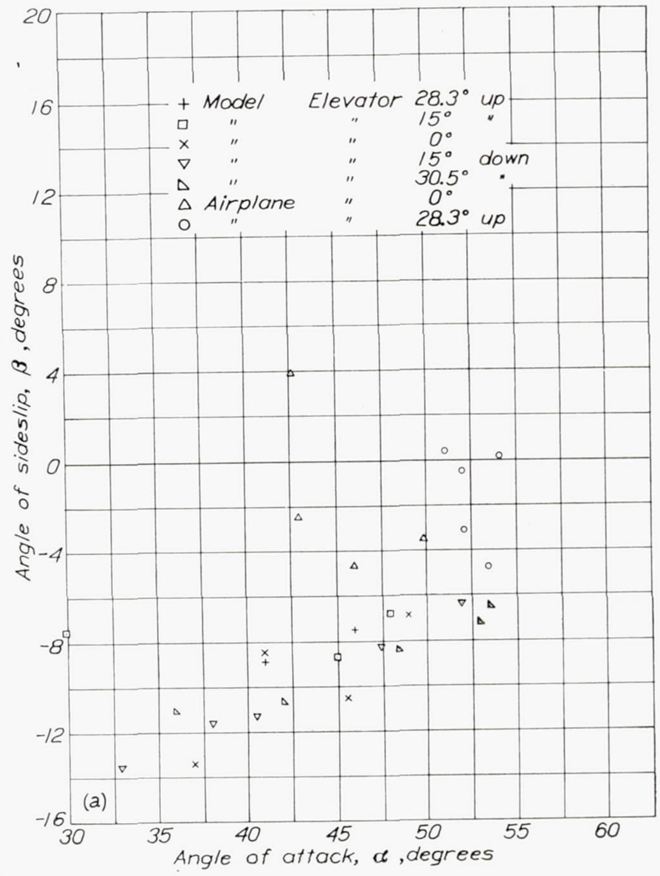


(a) F4B–2 surfaces, normal+radio+raft loading.

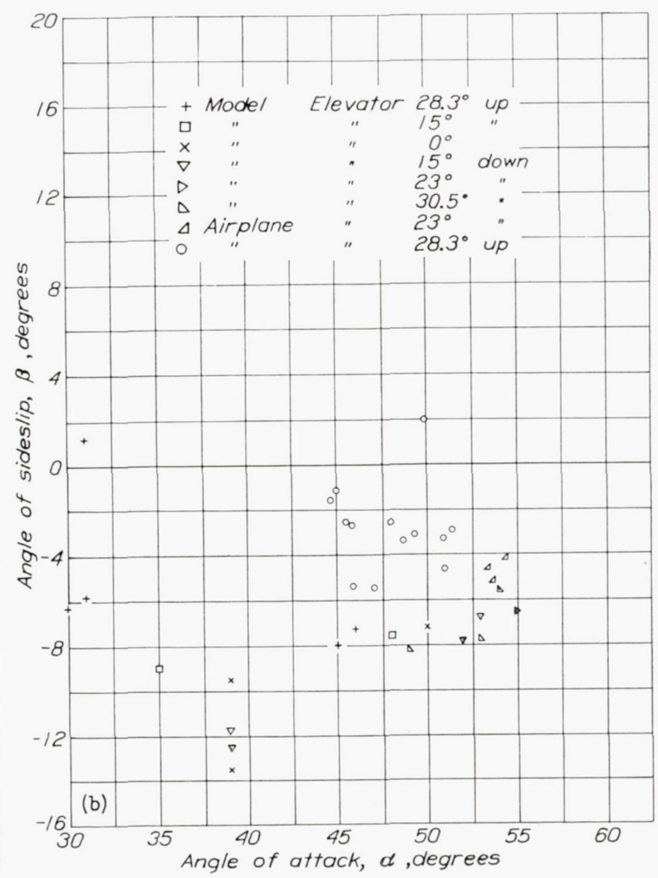


(b) F4B–4 surfaces, normal+radio+raft loading.

FIGURE 12.—Variation of angle of attack with rudder setting. F4B–2.

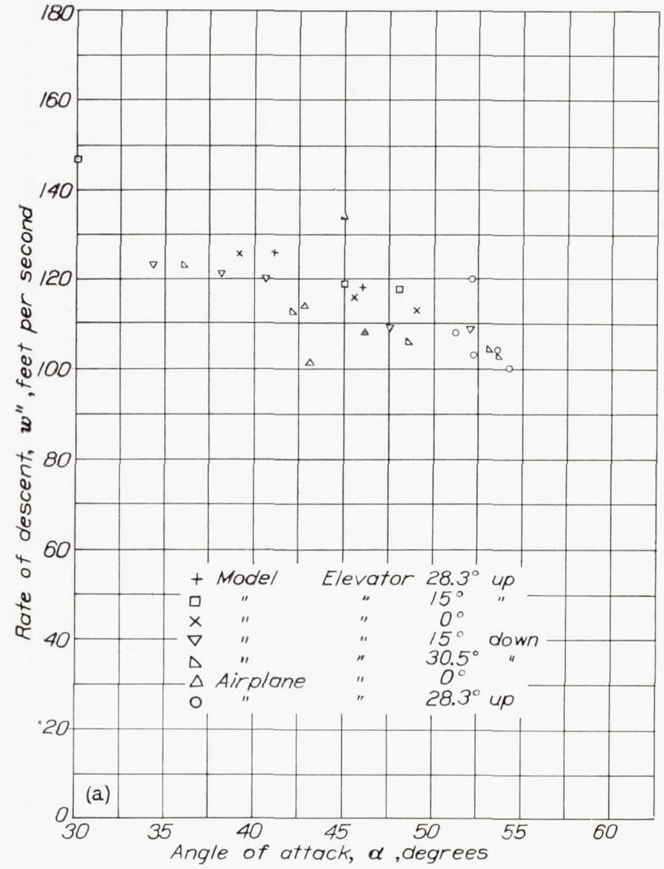


(a) F4B–2 surfaces, normal+radio+raft loading.

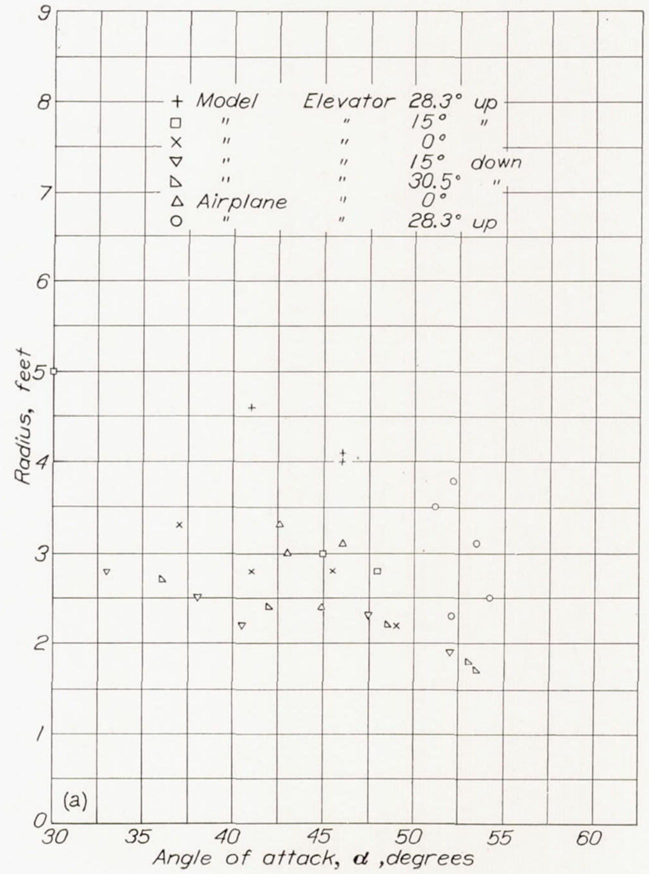


(b) F4B–4 surfaces, normal+radio+raft loading.

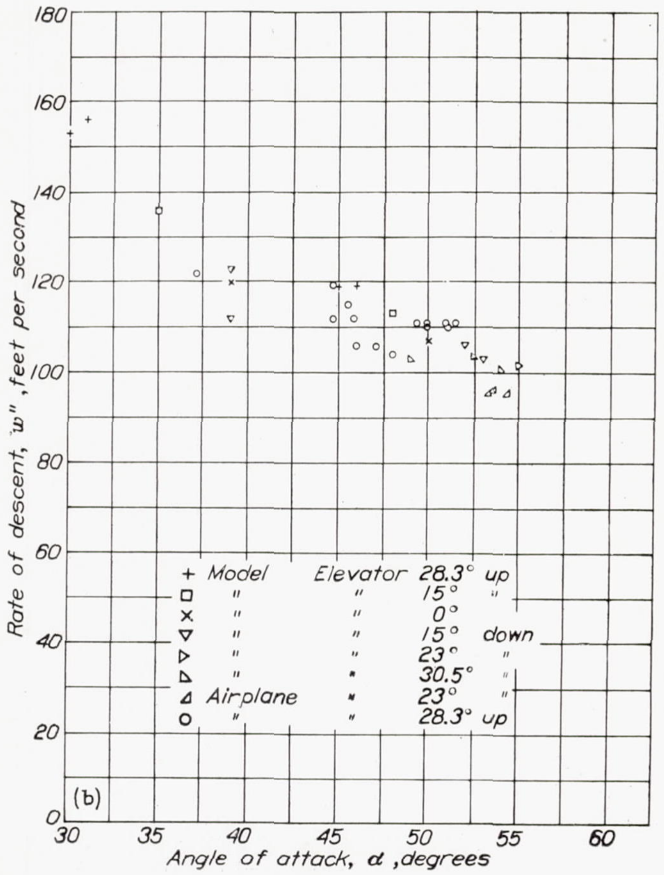
FIGURE 13.—Variation of angle of sideslip with angle of attack. F4B–2.



(a) F4B–2 surfaces, normal+radio+raft loading.

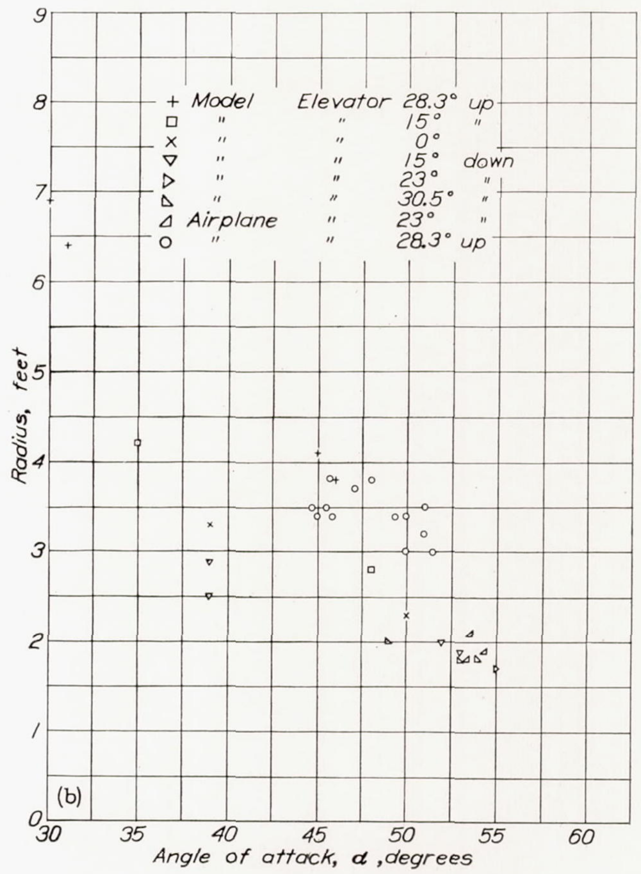


(a) F4B–2 surfaces, normal+radio+raft loading.



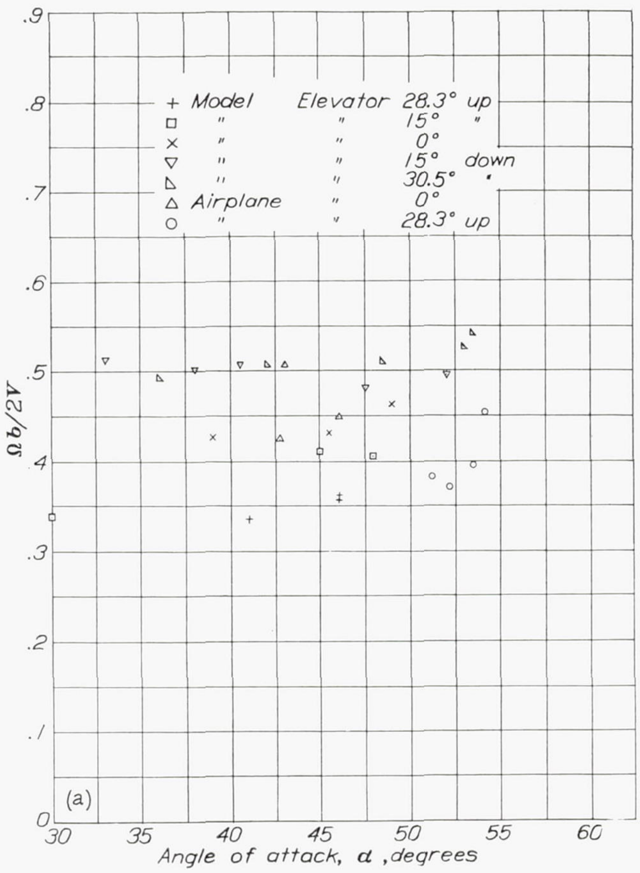
(b) F4B–4 surfaces, normal+radio+raft loading.

FIGURE 14.—Variation of rate of descent with angle of attack. F4B-2.

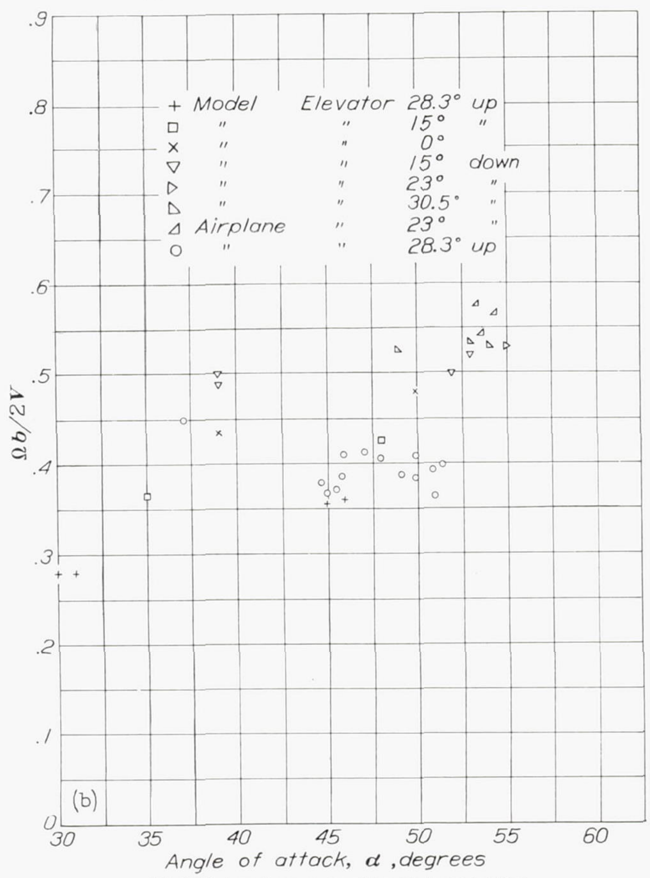


(b) F4B–4 surfaces, normal+radio+raft loading.

FIGURE 15.—Variation of radius with angle of attack. F4B–2.

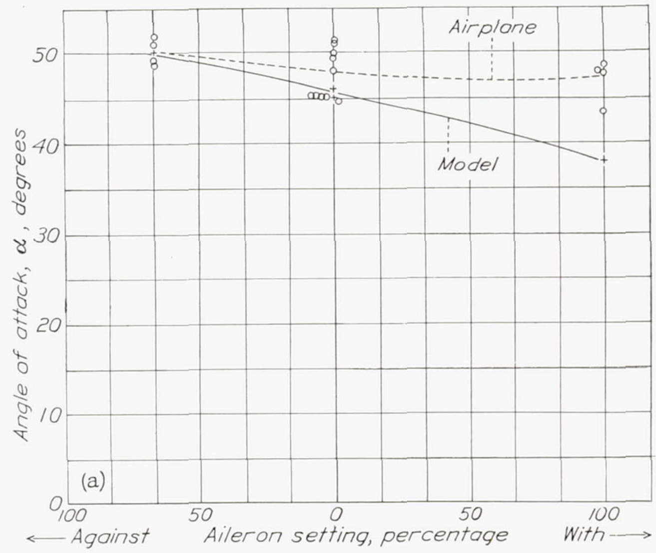


(a) F4B-2 surfaces, normal+radio+raft loading.

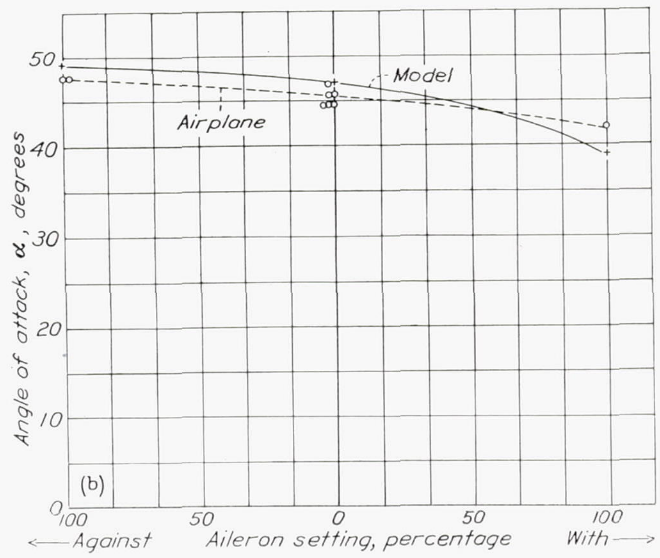


(b) F4B-4 surfaces, normal+radio+raft loading.

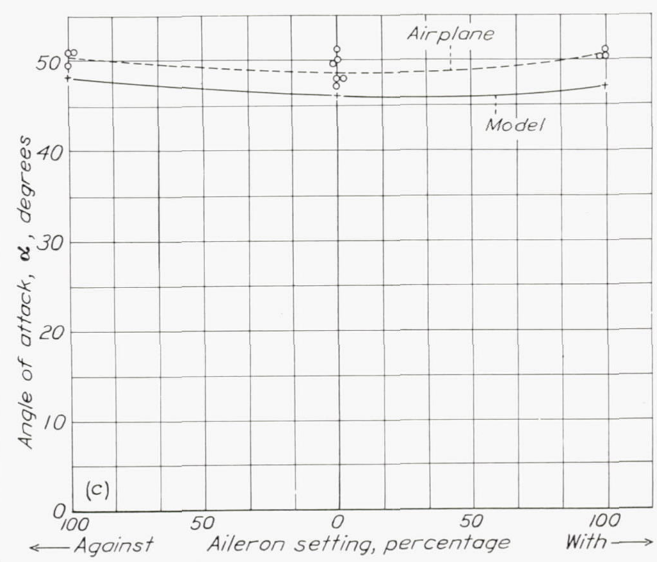
FIGURE 16.—Variation of $\Omega b/2V$ with angle of attack. F4B-2.



(a) F4B-4 surfaces, normal+radio+raft loading.

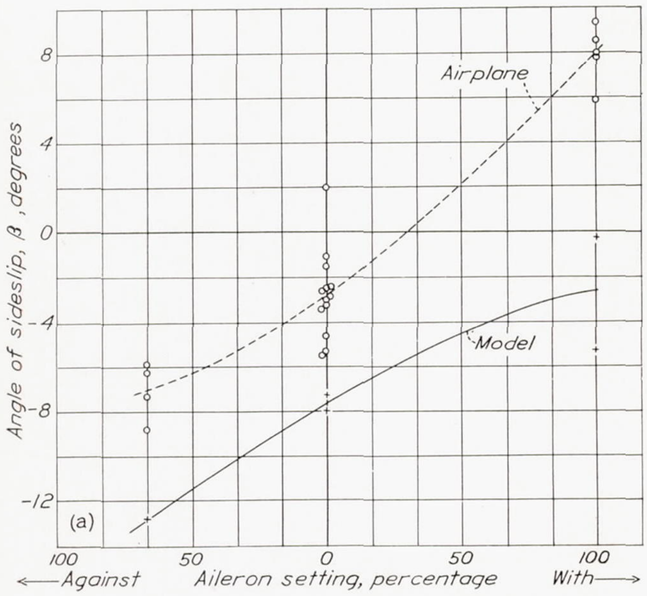


(b) F4B-4 surfaces, carrier overload.

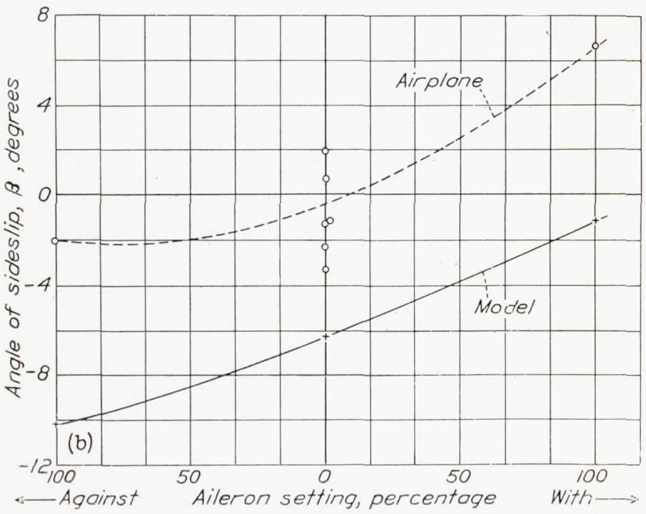


(c) F4B-4 fin, intermediate stabilizer, normal+radio+raft loading.

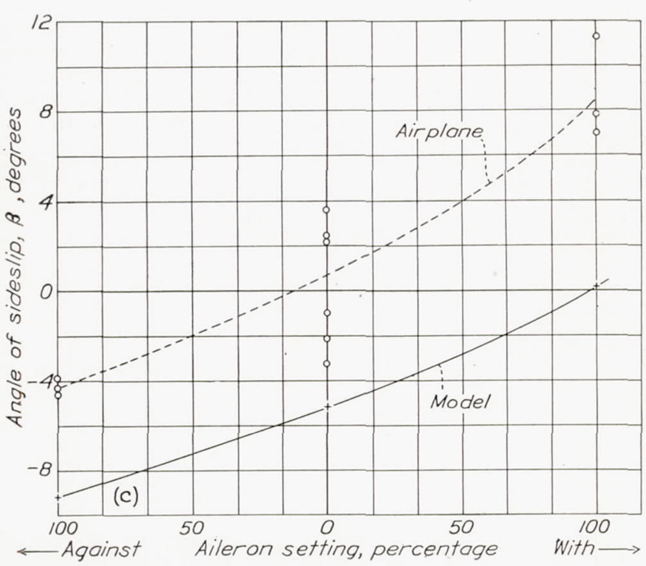
FIGURE 17.—Variation of angle of attack with aileron setting. F4B-2.



(a) F4B-4 surfaces, normal+radio+raft loading.

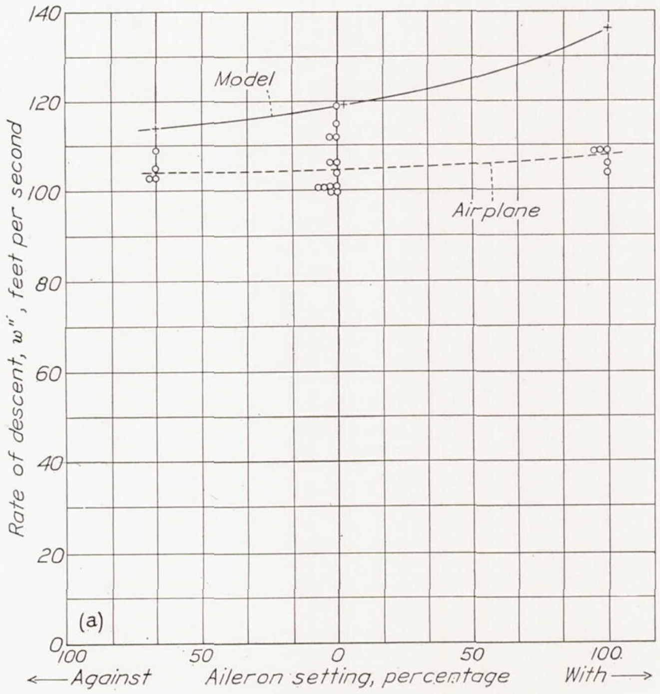


(b) F4B-4 surfaces, carrier overload.

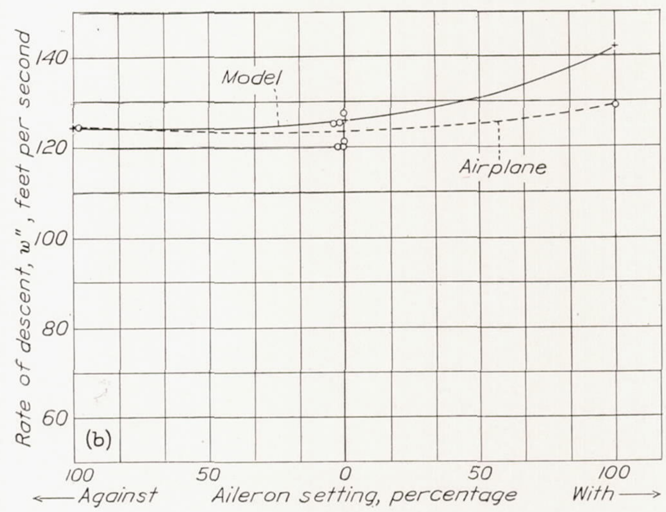


(c) F4B-4 fin, intermediate stabilizer, normal+radio+raft loading.

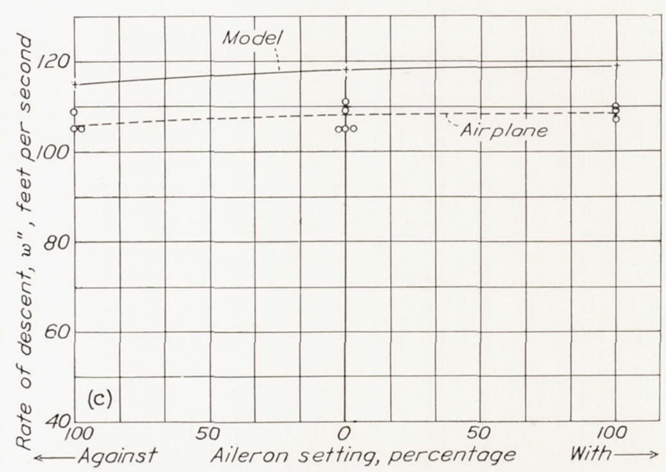
FIGURE 18.—Variation of angle of sideslip with aileron setting. F4B-2.



(a) F4B-4 surfaces, normal+radio+raft loading.

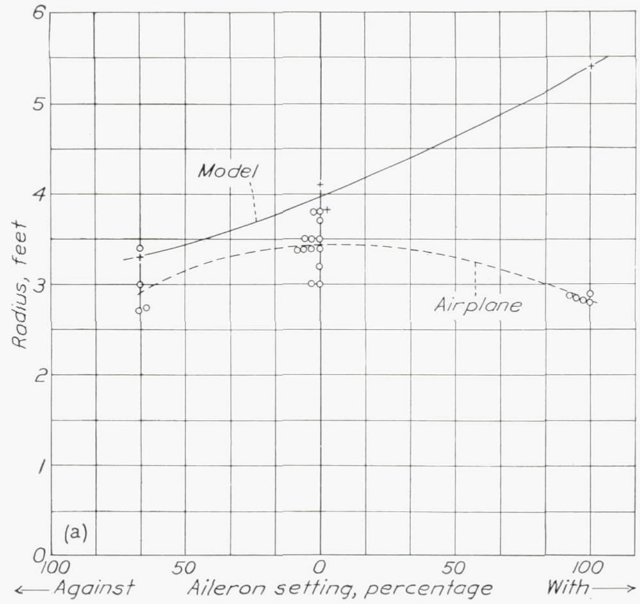


(b) F4B-4 surfaces, carrier overload.

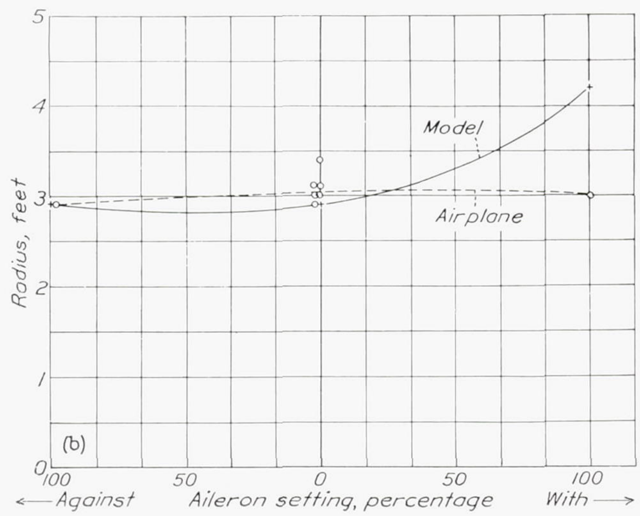


(c) F4B-4 fin, intermediate stabilizer, normal+radio+raft loading.

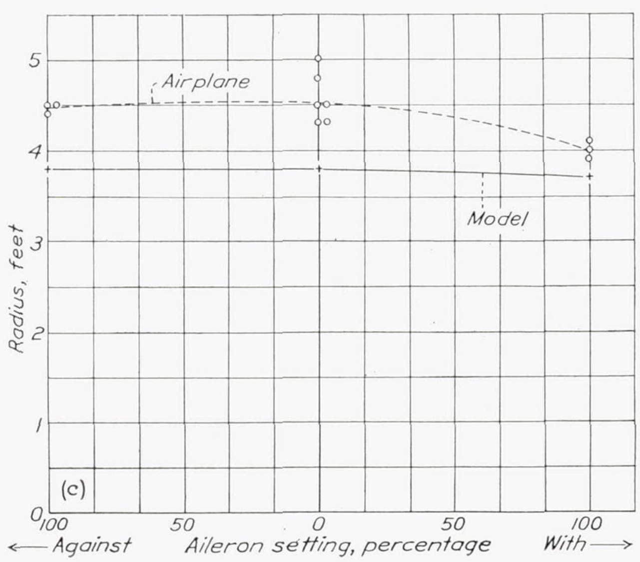
FIGURE 19.—Variation of rate of descent with aileron setting. F4B-2.



(a) F4B-4 surfaces, normal+radio+raft loading.

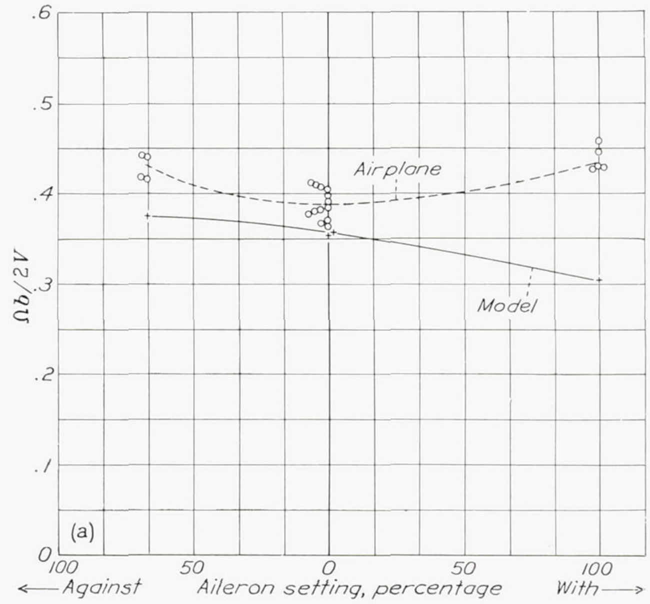


(b) F4B-4 surfaces, carrier overload.

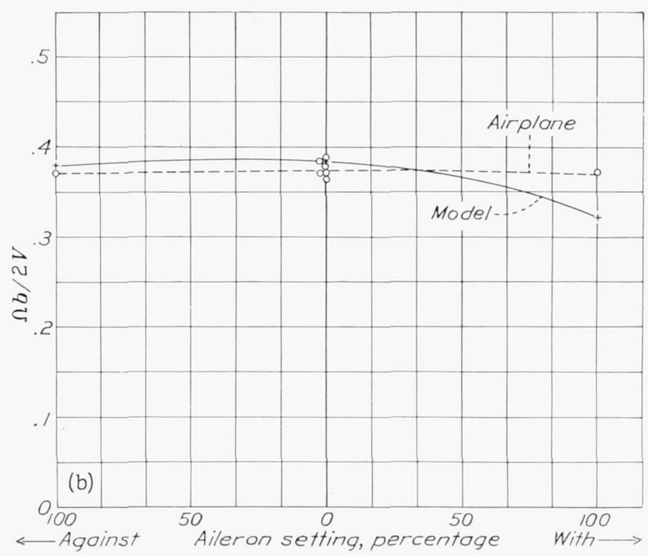


(c) F4B-4 fin, intermediate stabilizer, normal+radio+raft loading.

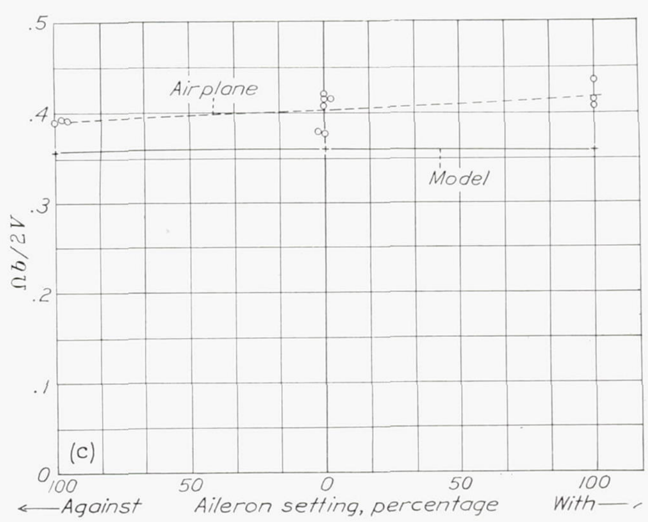
FIGURE 20.—Variation of radius with aileron setting. F4B-2.



(a) F4B-4 surfaces, normal+radio+raft loading.



(b) F4B-4 surfaces, carrier overload.



(c) F4B-4 fin, intermediate stabilizer, normal+radio+raft loading.

FIGURE 21.—Variation of $\Omega b/2V$ with aileron setting. F4B-2.

Recoveries.—Results of comparable recovery tests with the XN2Y–1 airplane and model are given in table III, in which the full-scale data were obtained from a series of tests the results of which have not been published. The given values are based in the camera records with the exceptions noted in the table. Similar results for the F4B–2 are given in table IV, the full-scale results of which were taken from reference 5.

Precision.—The test conditions were held within the following limits:

Control settings	$\pm 1\frac{1}{2}°$.
Weight	± 1 percent.
Moments of inertia	± 5 percent.
C_g and $\frac{z}{c}$	± 1 percent of chord.

These limits allow for errors in measuring values, changes due to temperature and humidity, and discrepancies permitted because of the time required to obtain more exact values.

The steady-spin data for the models are believed to be correct within the following limits:

Angle of attack	$\pm 3°$.
Angle of sideslip	$\pm 1\frac{1}{2}°$.
Air speed	± 2 percent.
Radius	± 10 percent.
$\Omega b/2V$	± 3 percent.

These limits allow for inaccuracies both in measurements and in method of reduction of the data. In cases where unsteady spins were obtained the data and limits apply to the mean values of the factors.

The recovery data for the models are believed to be correct within $\pm \frac{1}{4}$ turn.

The precision of the full-scale results is given in reference 5.

COMPARISON BETWEEN AIRPLANE AND MODEL RESULTS

Steady spins.—The XN2Y–1 model requires a somewhat greater rudder setting with the spin to attain a given angle of attack than did the airplane. The model spun with about 9° more outward sideslip than did the airplane at a given angle of attack throughout the angle-of-attack range. The model's rate of descent w'' (scaled to full-scale equivalent) was almost the same as that of the airplane at high angles of attack, but was about 10 percent greater at low angles. The model spin radius was somewhat shorter than that of the airplane at all angles of attack but the difference was more pronounced at the lower angles. The value of $\Omega b/2V$ for the model was in good agreement with that for the airplane throughout the angle-of-attack range.

For both model and airplane, deflecting the elevator down decreased the angle of attack but, for a given angle of attack, resulted in more outward sideslip, a lower rate of descent, a smaller radius, and a greater value of $\Omega b/2V$.

The comparison between airplane and model results for the F4B–2 is not clear-cut because both airplane and model were fairly unsteady in the spin. The scattering of the data from the flight tests indicates the nature of the results. The model results do not scatter so badly because they represent the mean condition in a prolonged spin. The following comparison is based on rough averages of the large number of full-scale points in figures 12 to 21.

The model required somewhat greater rudder setting with the spin to attain a given angle of attack than did the airplane. The model spun with about 5° more outward sideslip than did the airplane at a given angle of attack. The unsteadiness, which in some conditions was a definite oscillation, of the spins of both model and airplane was most apparent in the angle of sideslip. The rate of descent of the model was about the same as that of the airplane at the high end of the angle-of-attack range. No airplane data at the low angles of attack are available but, from the trend of the points at high and intermediate angles, the indications are that the model rate of descent was higher at the low angles of attack than that of the airplane would be. There was good agreement between the radii of spin at the same angle of attack within the limits of the data. The values of $\Omega b/2V$ were of the same order of magnitude for model and airplane.

For both model and airplane, moving the elevator down increased the angle of attack but, for a given angle of attack, made no definite change in sideslip, slightly decreased the rate of descent, decreased the radius, and increased $\Omega b/2V$.

Both model and airplane showed very little change in characteristics of the spin, except sideslip, with aileron movement when the stabilizer was at an intermediate height on the fin. Both model and airplane required from 9° to 15° more outward sideslip for spinning equilibrium with ailerons against the spin than with ailerons with the spin for the stabilizer both on the fin and in its normal location.

With the stabilizer in its normal location both model and airplane spun at lower angles of attack when the ailerons were with the spin than when they were neutral or against the spin. The change in angle of attack was much greater, however, for the model than for the airplane for both loadings tested. A similar, and related, discrepancy is apparent in the comparisons of effect of aileron setting on rate of descent; the rate of descent increased more rapidly with aileron setting against the spin for the model than for the airplane. The variation of radius and $\Omega b/2V$ with aileron setting for the carrier-overload condition was consistent with the variations of the other characteristics. With the normal+radio+raft loading the radius and $\Omega b/2V$ for the airplane varied in a manner opposite to what would be expected from the angle-of-attack variation when the ailerons were changed from neutral to with the spin. The model values of these characteristics varied consistently with the variations of the other factors, giving a marked discrepancy with the airplane data.

Recoveries.—The turns required for recovery by the XN2Y–1 model were between the number required for the airplane in a right spin and those required in a left spin for cases in which the elevator was up during the steady spin. When the elevator was down in the steady spin, the recovery required about twice as many turns when the rudder was reversed for the model as for the airplane, and no recovery was obtained with the model when the controls were neutralized as compared with four or five turns for recovery in the case of the airplane. Placing ballast at the wing tips increased the number of turns necessary for recovery for both airplane and model.

The F4B–2 model recovery tests indicated that the F4B–2 fin and rudder combination was much less effective in bringing about recovery when the rudder was reversed than was the F4B–4 fin and rudder combination and that no recovery would be effected if the elevator were put down at the same time. In the airplane tests, recovery required about one turn more with the F4B–2 surfaces with the elevator down than with the F4B–4 surfaces, and recovery could be accomplished in less than three turns with either set of surfaces. When the F4B–2 surfaces were neutralized in the spin, the model in no case recovered. The airplane recovered from left spins but not from right spins with this control movement.

The airplane was in some cases slow in recovering from left spins but recovered satisfactorily from right spins with the F4B–4 surfaces and the normal +radio+raft and carrier-overload loadings. The model recovered satisfactorily under the same conditions in all cases tried. Recoveries were slow and uncertain for all cases of neutralization of the model controls, and also for the airplane in right spins; but recovery was generally definite in left spins. Both model and airplane were slightly improved in recovery characteristics by the addition of auxiliary fin 2. The airplane showed greater improvement in recovery characteristics when the stabilizer was raised to an intermediate position on the fin than did the model. Increasing the loading increased slightly, in general, the number of turns for recovery of both model and airplane.

In the consideration of the results from model tests certain fairly obvious facts must be borne in mind. A scale model cannot be expected to check full-scale spinning characteristics more closely than the agreement between right- and left-hand spins of a symmetrically rigged airplane with the propeller locked. Neither can they be expected to check full-scale characteristics more closely than the check between two airplanes built from the same set of drawings. The most that can be expected is a positive indication as to whether the airplane will be definitely slow to recover or uncontrollable in the spin, will be a borderline case with the possibility of uncontrollable spins with slight changes in loading or rigging, or will recover quickly under all probable conditions of loading and rigging.

From the tables and figures included herein it is evident that the XN2Y–1 and F4B–2 models gave good approximations to the spinning behavior of the respective airplanes. There are certain consistent differences between the model and the airplane steady-spinning characteristics that are in agreement with indications from other sources (references 3, 10, 11, and 12) and that had, in part at least, been specifically predicted in reference 11. There is one marked discrepancy between model and airplane results–i. e., in the effect of the ailerons on the spin of the F4B–2 with the F4B–4 surfaces. In this case, however, the full-scale characteristics seem inconsistent among themselves. Despite the differences in attitude between the model and airplane spins, the models would apparently spin with any control setting that would produce a spin on the airplane with the possible exception of one or two cases where full-scale spins were obtained only after repeated attempts with complicated control movements.

The agreement between model and airplane recovery characteristics is better than for the steady spins. The XN2Y–1 model recovered positively, but not quickly, with reversal of the rudder as did the airplane. The model, however, indicated recovery to be slowest from spins with the elevator down. For the airplane this behavior was true of left spins, but the opposite was true of right spins. The model could not be counted on to recover with controls neutral and recovery was slow in any event. The same was true in a general way of the airplane.

The recovery characteristics of the F4B–2 model with the F4B–2 fin and rudder were very poor, recovery not being possible with simultaneous reversal of both rudder and elevators although it could be effected by reversal of the rudder first and the elevator afterward. The indications from the model behavior are that relatively inexperienced pilots or pilots trained to make recoveries in a standard manner (i. e., by holding the elevator full up and the rudder full with the spin during the steady spin followed by simultaneous and quick reversal of both controls) would have difficulty with spins and such was apparently the case when the airplane was placed in service. The model indicated decidedly poorer recovery characteristics with these surfaces than did the F4B–2 airplane tested at Langley Field. The model recovered satisfactorily with all the other tail combinations when the rudder was reversed. Model recoveries were, in general, more positive with these latter tail combinations than recoveries with the airplane.

The model definitely would not recover when the controls were neutralized with the F4B–2 surfaces. Recoveries were slow and uncertain with the airplane. When the controls were neutralized with the F4B–4 fin and rudder, recoveries were slow and uncertain for both model and airplane.

Although the results of the tests with the two biplane models reported herein are very encouraging, the tests are not sufficiently general to warrant definite conclusions. Both models have quite similar general arrangements. An additional series of comparisons similar to those reported should be made with at least one dissimilar arrangement, preferably a monoplane. Only experience with a large number of models will give a true indication of the reliability of the results. It is too much to expect that the model results will be infallible. The present indications are, however, that the results are worthy of a certain amount of confidence and that carefully conducted tests should prove of great value in estimating spinning characteristics.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *October 29, 1935.*

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TABLE I

COMPARISON OF AIRPLANE AND MODEL DATA

STEADY SPINS FOR THE XN2Y–1

[A, airplane; M, model]

Loading condition	Control setting			α		β		w''		Radius		$\Omega b/2V$	
	Aileron	Rudder	Elevator	A	M	A	M	A	M	A	M	A	M
				°	°	°	°	*ft./sec.*	*ft./sec.*	*ft.*	*ft.*		
Normal	Neutral	41° with	Up	60.5	58	13.4	0	78.2	81.8	1.6	1.9	0.620	0.562
Do	do	18° with	do	57.4	53	9.7	−5.7	79.0	85.6	2.2	2.4	.551	.523
Do	do	4° with	do	45.7	38	.7	−10.1	85.8	101	4.0	5.1	.449	.392
Do	do	41° with	Down	51.3	56	2.0	−6.7	81.3	77.5	2.2	1.6	.575	.661
Ballast at tips	do	8° with	Up	43.0	39	[a] 3.9	−11.1	88.5	98.0	4.7	4.9	.416	.419

[a] This value is believed by fight investigators to be questionable.

TABLE II
COMPARISON OF AIRPLANE AND MODEL DATA
STEADY SPINS FOR THE F4B–2

[A, airplane; M, model]

Loading condition	Tail combination	Control setting			α		β		w''		Radius		$\Omega b/2V$	
		Aileron	Rudder	Elevator	A	M	A	M	A	M	A	M	A	M
					°	°	°	°	ft./sec.	ft./sec.	ft.	ft.		
Stripped	B–4	Neutral	With	Up	44.5	47	−1.7	−6.2	111	118	3.9	3.8	0.376	0.356
Normal+radio+raft	B–2	do	do	do	52.6	46	−1.6	−7.5	107	118	3.1	4.1	.404	.360
Do	do	do	Neutral	Neutral	44.2	39	−1.7	−11.0	114	126	3.0	3.1	.449	.428
Do	B–4	do	With	Up	45.3	46	−2.0	−7.3	115	119	3.5	3.8	.373	.360
Do	do	do	do	¾ down	53.7	55	−4.6	−6.5	95.5	102	1.9	1.7	.563	.530
Do	do	With	do	Up	47.1	38	7.9	−2.8	107	136	2.8	5.4	.439	.305
Do	do	⅔ against	do	do	50.1	50	−7.1	−12.8	105	114	3.0	3.3	.436	.376
Do	do	Neutral	do	do	49.3	46	−3.2	−7.3	109	119	3.4	3.8	.395	.360
Do	Intermediate stabilizer	do	do	do	48.9	46	−.3	−5.2	107	119	4.6	3.8	.401	.360
Do	do	do	do	Down	47.3	49	−2.1	−7.9	103	110	3.7	2.1	.520	.495
Do	do	Against	do	Up	50.5	48	−4.3	−9.2	106	115	4.5	3.8	.392	.357
Do	do	With	do	do	50.6	47	8.7	.1	109	119	4.0	3.7	.418	.358
Do	B–4+fin 2	Neutral	do	do	48.9	43	−.8	−8.5	110	124	3.7	4.1	.363	.353
Carrier overload	B–4 fin	do	do	do	45.3	47	0	−6.3	123	126	3.1	2.9	.374	.383
Do	do	Against	do	do	47.7	49	−2.1	−10.2	124	124	2.9	2.9	.370	.378
Do	do	With	do	do	42.2	39	6.6	−1.2	129	142	3.0	4.2	.372	.322
Do	B–4+fin 3	Neutral	do	do	46.4	47	.2	−5.3	114	130	3.8	3.2	.373	.355

TABLE III
COMPARISON OF AIRPLANE AND MODEL DATA
RECOVERIES FOR THE XN2Y–1

Loading condition	Original setting		Final setting		Turns required for recovery		
	Rudder	Elevator	Rudder	Elevator	Airplane, right	Airplane, left	Model
Normal	With	Up	Neutral	Neutral	6,[a] 6,[a] 3½	3, 2½, 3	3½,[a] 4½, 5.
Do	do	do	Against	Down	3, 3, 3¼	1¾, 1¾, 1⅝	2½, 2¾.
Do	do	Down	Neutral	Neutral	5, 5¼, 3½	5, 4, 4¾	13,[a] ∞,[a] ∞.[a]
Do	do	do	Against	Down	2⅛, 2⅜, 2⅜	1¾, 2¼, 2¼	4,[a] 3, 4.
Ballast at tips	do	Up	Neutral	Neutral	8,[a] 9,[a] 9[a]	4½, 3½, 5½	6,[b] 6, 6.
Do	do	do	Against	Down	4½, 4¾, 4½	2¾, 1¾, 2¾	3, 3.

[a] No recovery in turns indicated. In the case of the model the spin was stopped by encounter with the safety net.
[b] Observer's estimate.

TABLE IV
COMPARISON OF AIRPLANE AND MODEL DATA
RECOVERIES FOR THE F4B–2

Loading condition	Tail combination	Control setting			Turns required for recovery		
		Aileron	Rudder	Elevator	Airplane, right	Airplane, left	Model
Stripped	B–2 fin	Neutral	Against	Down	2½	2	∞,[a] 6.[a]
Do	do	do	do	Neutral	2½	1½	3½,[a] 4, 5,[a] 4.[a]
Do	do	do	do	Up	2⅜	2	2,[a] 2,[a] 1¾, 2.
Do	do	do	Neutral	Neutral	6[a]	2¾	∞,[a] ∞.[a]
Do	B–4 fin	do	Against	Down	1½, 1¼, 1½	½, 1⅛, 1⅛	1¼, 1¼, 1¾.
Do	do	do	do	Neutral	1¾	1¼	1, 1.
Do	do	do	do	Up	1½, 1½, 1⅞	2¾, 1¼, 2, 1⅝	1, 1.
Do	do	do	Neutral	Neutral	2½, 1⅞, 4, 6	1, ¾, 3, 3¼	3,[a] 3,[a] 3.[a]
Do	B–4+fin 2	do	Against	Down	1½, 1½	1½, 1¼	1, 1¼.
Do	do	do	Neutral	Neutral	4½, 3¾	5, 1⅜	3, 2.[a]
Do	B–4+fin 3	do	Against	Down	1⅞	1⅛	1½, 1¼.
Do	do	do	do	Neutral	1¾	1¼	1½.
Do	do	do	do	Up	2¼	3⅜	¾, ¾, ¾.
Do	do	do	Neutral	Neutral	6,[a] 6½[a]	1¾, 1¾	4,[a] 3.[a]
Normal+radio+raft	B–4 fin	do	Against	Down	1⅝, 1½, 2	2, 1½, 1¾	1¼, 1½, 1.
Do	do	do	do	Neutral	1½, 2	1¼, 1¼	1, 1¼, 1¼.
Do	do	do	do	Up	1¾	3⅛, 1½, 2¼, 3, 2½, 3½, 4½, 3½, 2½, 1½, 2¼, 1¾.	1,[a] 1, 1.
Do	do	do	Neutral	Neutral	5, 8½, 6[a]	2, 3, 2	2¼,[a] 3,[a] 3½.[a]
Do	Inter. stab	do	Against	Down	1, 1, 1		1¼, 1½, 1½.
Do	do	do	do	Neutral	1⅛, 1⅜	1⅛, 1⅛	1½, 1¼, 1.
Do	do	do	do	Up	1¼, 1⅛	1, 1⅜, 1¼, ⅞, 1⅛	1, 1, ¾.
Do	do	do	Neutral	Neutral	4⅜, 5[a]	2, 4½	3.[a]
Carrier overload	B–2 fin	do	Against	Down	2⅝	2⅞	5,[a] 6,[a] ∞.[a]
Do	do	do	do	Neutral	4¼	2	6,[a] 4, 3½.
Do	do	do	do	Up	6[a]	4	2,[a] 2,[a] 2½.
Do	do	do	Neutral	Neutral	8[a]	3½	∞.[a]
Do	B–4 fin	do	Against	Down	2 1¾, 2, 1¾, 2¼	1½, 1½, 1½, 2, 1½	2, 1½, 2¼.
Do	do	do	do	Neutral	1, ¾, 2	1⅜, 1¼	1¼, 1½, 1¼.
Do	do	do	do	Up	1¾, 1½, 1¾	2⅝, 6,[a] 1¾, 4, 2, 5, 3, 1½, 2¼, 1½.	1¼, 1.[a]
Do	do	do	Neutral	Neutral	10,[a] 12,[a] 7[a]	2¼, 2¾, 2, 2½	5.[a]
Do	B–4+fin 2	do	Against	Down	1⅜, 1½	1⅜, 1¼	1¼.
Do	do	do	do	Neutral	1½, 1¼	1, 1¼	1, 1.
Do	do	do	do	Up	1⅝, 1½	1¼, 1¼	1, 1.
Do	do	do	Neutral	Neutral	4¾, 6[a]	4, 4	2, 2½.[a]
Do	B–4+fin 3	do	Against	Down	1¾	1½	1¼, 1.
Do	do	do	do	Neutral	2	1½	1¼, 1, 1.
Do	do	do	do	Up	1¾	5½, 1½	1¼.
Do	do	do	Neutral	Neutral	6[a]	2¾	3, 7.[a]

[a] No recovery in turns given. In the case of the model the spin was stopped by encounter with the safety net.

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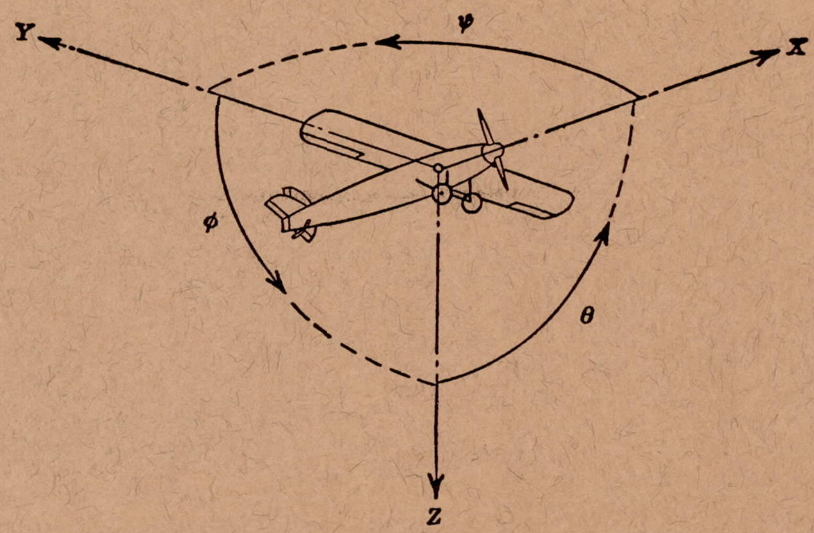

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$$C_l = \frac{L}{qbS} \text{ (rolling)} \qquad C_m = \frac{M}{qcS} \text{ (pitching)} \qquad C_n = \frac{N}{qbS} \text{ (yawing)}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter

p, Geometric pitch

p/D, Pitch ratio

V', Inflow velocity

V_s, Slipstream velocity

T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$

Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$

C_s, Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$

η, Efficiency

n, Revolutions per second, r.p.s.

Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.

1 metric horsepower = 1.0132 hp.

1 m.p.h. = 0.4470 m.p.s.

1 m.p.s. = 2.2369 m.p.h

1 lb. = 0.4536 kg.

1 kg = 2.2046 lb.

1 mi. = 1,609.35 m = 5,280 ft.

1 m = 3.2808 ft.